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Likelihood Analysis of sub-TeV Gamma-rays from RXJ1713-39 with CANGAROO-II

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Abstract. We have detected gamma-rays from RXJ1713−39 in the energy range between 400 GeV and 5 TeV using a new kind of analysis: likelihood analysis. The statistical significance of the measurement is greater than 8 σ. The details of this analysis method are presented.

1 Introduction

The CANGAROO experiment is the Imaging Atmospheric Cherenkov Telescope located in Woomera, South Australia. It started with a 3.8-m telescope (Kifune et al., 1995). We now have a 10-m reflector (Kawachi et al., 2001) and are going to build a stereo-scopic system (Mori et al., 2001).

Supernova remnants are one of the hot topics related to origin of cosmic rays (Yanagita, 1999; Ellison et al., 2000). The CANGAROO experiment detected gamma-rays from SN1006 (Tanimori et al., 1998a, 2001; Hara et al., 2001). Particle acceleration by a shock wave produced by a supernova explosion and inverse Compton scattering with micro-wave background radiation (Pohl , 1996; Mastichiadis, 1996a; Mastichiadis and de Jager , 1996b; Yoshida and Yanagita, 1997; Naito et al., 1999) can explain cosmic ray acceleration very well.

RXJ1713−39 was found in the ROAST all sky survey (Pfeffermann and Aschenbach , 1996), and was found to have a shell structure. Hard X-ray emission was observed by ASCA (Koyama et al., 1997). An association with a molecular cloud was found (Slane et al., 1999). The CANGAROO collaboration found an evidence for TeV gamma-ray emission from the northwest-rim (Muraishi et al., 2000). The preliminary result of CANGAROO-II (7m) observation in 1999 shows indication of a gamma-ray signal. In this report, an analysis of RXJ1713−39 with CANGAROO-II (10m) is presented.

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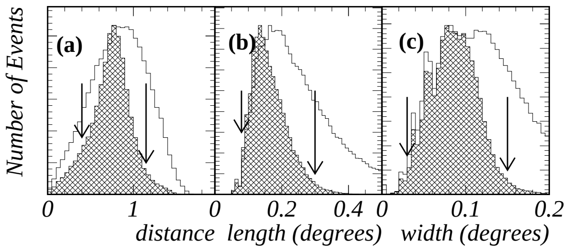

Fig. 1. Shape parameter distributions: (a) $distance$, (b) $length$, and (c) $width$. The blank histograms were obtained from the OFF-source run. The hatched histograms are Monte-Carlo gamma-ray events. The cut positions are indicated by arrows.

2 Analysis

2.1 Data sample

The observation was carried out during two periods: 23–26 July and 19–27 August, 2000. The pointing direction was as same as that of CANGAROO-I observation (Muraishi et al., 2000), i.e., the NW-rim (RA, δ)=($17^h11^m56^s.7$, $-39°31'52''.4(J2000)$), where the X-ray flux is maximum. The total observation periods were 1419 and 1397 min., for ON- and OFF-source runs, respectively. We restricted the data to that taken at elevation angles greater than 60 degrees and without cloud, dew etc., by looking carefully at the proton shower rate. The resulting good quality data corresponded to 649 and 642 min. for ON- and OFF-source runs, respectively. After removing bad (hot) PMT and bright star hits, we applied a pulse height cut (~ 3.3 photoelectrons) and a timing cut ($\pm 40nsec$). Events with at least one cluster of five-adjacent triggered PMTs were then analyzed.

2.2 Conventional Imaging Cut

First we rejected energetic multi-cluster events as follows. We calculated the energy-ratio (E_{other}/E_{max}) between the most energetic cluster (E_{max}) and the others (E_{other}). Because the gamma-ray events most likely have a single cluster, we rejected events with this ratio greater than 25%. Then, the event shape parameters (Hillas, 1985; Weekes et al., 1989) of $distance$, $length$, $width$, $asymmetry$ and α were calculated for the most energetic clusters (Fig 1). The blank histograms are obtained from the OFF-source run. The hatched histograms are Monte-Carlo gamma-ray events. The cut positions are indicated by the arrows. Here, we refer to this as a $square\ cut\ analysis$. The cut dependences of the α distributions are shown in Fig 2: Fig 2-(a) was obtained without any shape cuts, and (b) was obtained by a $distance$ cut. By adding $length$ and $width$ cuts, we obtained Fig 2-(c). The data points with statistical error bars were obtained by ON-source runs, and the hatched histogram by OFF-source runs, respectively. Better signal-to-noise ratios (S/N-ratios) were obtained by tighter cuts. The normalization of OFF events was done using the number of events with $\alpha > 25$ degrees. This agreed with the time-interval ratios between the ON- and OFF-source runs. The obtained signal levels were: (a) $1510 \pm 234 (6.4\sigma)$, (b) $1129 \pm 169 (6.7\sigma)$, and (c) $931 \pm 127 (7.3\sigma)$, respectively.

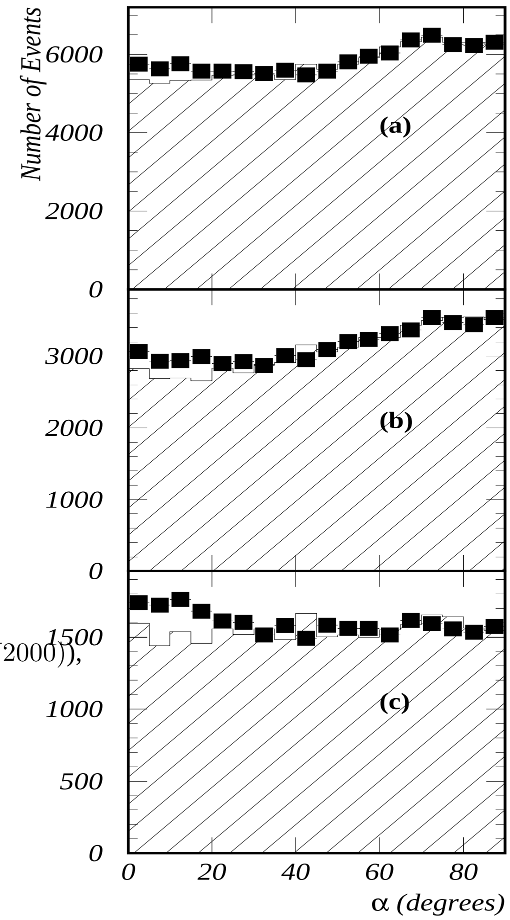

Fig. 2. Image orientation angle (α) distributions for ON-source data (solid squares) and OFF (hatched histogram), for a "square cut" analysis; (a) no cut, (b) $distance$ cut, and (c) ($distance$, $length$, and $width$) cut.

2.3 Likelihood

It is well known that there are energy dependences in the standard shape parameters (Hillas et al., 1998). One way to minimize these effects is a likelihood analysis (Enomoto et al., 2001). Before doing this, we have observed a strong correlation between the $distance$ and the other shape parameters. This is considered to be due to the edge effect of the focal plane detector (i.e., camera). We, therefore, need a $distance$ cut before starting a likelihood analysis. Because the $distance$ also has a small energy dependence, we

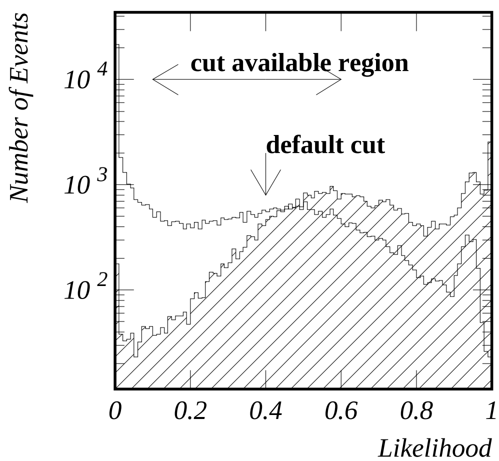

Fig. 3. Likelihood distributions for Monte-Carlo gamma rays (the hatched region) and OFF-source events (the blank histogram).

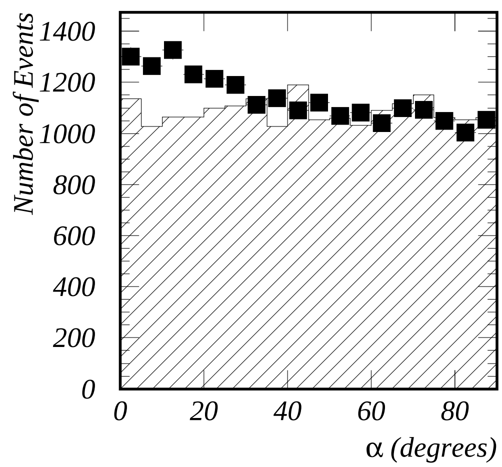

Fig. 4. Image orientation angle (α) distributions for ON-source run (data points with error bars) and OFF (hatched histogram) for a likelihood cut analysis.

corrected it by a linear function of energy. After applying an energy-dependent $distance$ cut, we calculated the likelihood using the above shape parameters ($length$, $width$, and $asymmetry$) for both gamma-ray and proton assumptions. In order to estimate the gamma-ray probability-density-function (PDF), we used Monte-Carlo gamma-ray events; for protons, the OFF-source events were used. In the Monte-Carlo simulation, gamma-rays with a Crab-like spectrum ($E^{-2.5}$) were generated. In practice, we made two-dimensional histograms, for example, $log(ADC)$ vs $length$. We assumed that ADC is proportional to the energy of the showers. The total number of events was normalized to unity and two-dimensional (2D) PDFs were obtained. We defined the likelihood-ratio (L) as

$$L = Prob(\gamma)/(Prob(\gamma) + Prob(p))$$

, where, $Prob$ means product of 2D-PDFs of each shape parameter for the gamma-ray or proton assumption. Here, a one-to-one contamination of gamma-rays to protons was assumed (this can be modified in the future), in spite of the fact that protons are dominant in cosmic-rays. The distributions of L are shown in Fig 3. The hatched histogram was L for Monte-Carlo gamma-rays and the blank OFF-source events. The final event samples were obtained by cutting events with $L > 0.4$, which is indicated by the arrow in Fig 3. The resulting α distribution is plotted in Fig. 4. The data points with statistical error bars were obtained by ON-source run, and the hatched histogram by OFF-source run, respectively. The number of excess events was 946±108(8.7σ). In order to check the algorithm, we tried changing the background sample, i.e., from OFF- to ON-source events to make proton PDFs. The number of excess events changed to 938±108(8.7σ), allowing us to conclude that there are no event-specific biases. The S/N-ratio was greatly improved by this analysis. The energy threshold for this analysis was estimated to be 400 GeV with the present CANGAROO-II system.

The α distribution is wider than that for a point source assumption (typically within $15°$), consistent with the previous observation (Muraishi et al., 2000). Roughly speaking, the observed flux agrees with the previous observation (Muraishi et al., 2000). A more precise flux calculation is now being carried out, based on the following systematic error studies.

3 Possible Systematics

Here, we discuss the possible systematic errors in the acceptance calculation using this likelihood method. The acceptance was calculated using the Monte-Carlo method (Enomoto et al., 2001). Gamma-rays with a Crab-like spectrum ($E^{-2.5}$) were generated. The measured values of the detector parameters, such as the point spread function (PSF) of the mirrors, the reflectivity, etc. we used. In order to check, we analyzed Crab data (observed in December 2000 with the 10-m telescope) and compared the obtained flux with previous measurements (Tanimori et al., 1998b; Aharonian et al., 2000). They are consistent with each other within 12% at ~ 3 TeV. On the other hand, the statistical error of the Crab measurement was 17%. In order to check cut dependence of the analysis, we also changed the cut value of L, the clustering methods, and the threshold, and obtained the fluxes each time. From the above procedures, we estimated a systematic uncertainty of 15.4%. The stable region of L in the accep-

tance calculation is shown in Fig 3 by the horizontal arrow. The acceptance is considered to be stable within 6.5% in this region with respect to the L cut.

3.1 Energy Spectrum

For the energy scale ambiguities, we considered the error on mirror reflectivity, PSFs, the effects of Mie scatterings, and the ambiguity on the single-photon pulse height. The estimated value was 20%.

3.2 Angular Resolution

The pointing error of the telescope system can be checked by looking at bright stars in various observation periods. To date, we have only had bright stars beyond one-degree from the centre of the field of view where there were significant edge effects and aberrations. For now we have adopted a systematic error of 0.1 degree.

4 Discussion

An improvement in the S/N-ratio was clearly demonstrated so far. Generally speaking, the gamma-ray signal increased with the background remaining the same, when compared with the traditional square cut.

As for the $asymmetry$ parameter, only a positive or negative cut can be applied in the $square\ cut\ analysis$, greatly reducing the number of events accepted. However, a likelihood analysis can save this situation. Almost all of the parameters can be put into the PDFs, even if there are small differences between gamma-rays and protons. It is necessary, however, to be careful of the dependencies between the various parameters.

The most important thing is that this kind of analysis can reduce any "human bias", because the number of cut parameters is very small. The systematic error, therefore, should be smaller than the $square\ cut\ analysis$. The small number of cut parameters makes it easy to estimate the systematic errors.

Usually, the cut value of L should be around ~ 0.5; allowing automated analysis for any situations such as different elevation angles, etc. For the analysis of stereoscopic observations (Enomoto et al., 2001), the product of L of many telescopes can be used as a single-cut parameter. In this case it is necessary to tune the Monte-Carlo simulations as accurately as possible.

5 Conclusion

We have measured gamma-rays from RXJ1713−39 in the energy range between 400 GeV and 5 TeV. The statistical significance of the measurement is greater than 8 σ. We have used the new likelihood method of analysis. We obtained a better signal-to-noise ratio compared with the standard analysis. Also we confirmed the systematic error of this analysis is sufficiently small.

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